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ANALYSIS

Measuring transnational leakage of forest conservation

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ABSTRACT

Forest conservation in one country can influence the degree of conservation or deforestation in other countries because of international linkages of the forest products industry and markets and a lack of global coordination. Thus leakage and offsetting losses of environmental quality may be present. This paper develops an analytical framework for measuring this leakage and estimates its magnitude via general equilibrium modeling. We find that the magnitude of leakage depends upon the price elasticities of supply of and demand for forestry products across the countries and degree of cooperation in forest conservation. We estimate that a significant portion (42%–95%) of the reduced forestry production implemented in a country/region can be transferred to elsewhere, offsetting environmental gains. Leakage generally diminishes as more countries cooperate, but cooperation among only a few countries does not always dramatically reduce leakage. Thus forest conservation efforts and associated environmental quantity gains in a country or group of countries can be seriously undermined in terms of global net conservation gain in the absence of effective global cooperation. Our results also point to the importance of taking leakage into account in evaluating local or regional forest carbon sequestration projects.

1. Introduction

Forest conservation in one place stimulates timber harvest or deforestation elsewhere (Sedjo, 1995; Sohngen et al., 1999). This phenomenon is often referred to as "leakage" particularly in the context of carbon sequestration (Intergovernmental Panel on Climate Change, 2001; Murray et al., 2004). Such leakage can significantly undermine the net gain in global forest conservation obtained from implementing conservation in a country (Berlik et al., 2002; Mayer et al., 2005). While such leakage has been recognized, few studies have attempted to empirically measure it particularly at the global level. This paper develops an analytical framework for measuring the global leakage associated with a local forest conservation effort and provides empirical estimates of the magnitude. These results offer insights into the efficacy of unilateral forest conservation efforts and provide policy implications for more effective global forest conservation.

Forest conservation leakage arises due to a variety of reasons. These include imbalance of regional conservation programs and forest conditions; features of conservation programs; and market factors including trade, along with many others (Murray et al., 2004). Leakage can occur in many

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settings. Contributions in the literature have addressed forestry leakage with most focusing on the carbon sequestration context. Murray et al. (2004) studied market forces that affect carbon leakage and developed a conceptual model. They also constructed empirical leakage estimates for example US forest carbon sequestration programs using their model along with econometric and sector-optimization modeling approaches. Their estimated leakage rates varied with program and region with a range from less than 10% to over 90%, suggesting the importance of accounting for leakage in forest policy design and analysis. Chomitz (2002) assessed and compared carbon leakage in land use change/forestry (LUCF) and energy projects. He found that there was no systematical difference in the likelihood of leakage between the LUCF and the energy projects, instead finding that the magnitude of leakage depends on how the project is integrated with the broader physical and economic system. Using a global timber market model, Sedjo and Sohngen (2000) evaluated the potential leakage of global forest carbon sequestration from the establishment of large-scale carbon plantations. Their study revealed that the leakage from the carbon plantations would be modest (less than 16%). Alig et al. (1997) examined the role of forests in carbon sequestration in the US using a multiregional and multisectoral model and found that carbon benefits attained from US afforestation would be considerably offset, primarily by conversion of forestlands to agricultural uses. Other related literature includes the leakage related synthesis by Schwarze et al. (2002) and the qualitative analyses of leakage potential and the value of leakage reductions by Aukland et al. (2003) and Geres and Michaelowa (2002).

Several studies addressed leakage in the context of non-carbon related forest conservation. Wear and Murray (2004) analyzed the effect of US Pacific Northwest public forest conservation on US and Canadian regional forest production and markets. They found that about 43% of the reduced public harvest timber would be replaced by increased harvest on Pacific Northwest private timberlands, 15% more elsewhere in the US for a US total of 58% and an additional 26% in Canada for a grand total of 84% (Murray et al., 2004). Findings from other studies, which though were not directly intended for qualifying leakage, are also indicative of leakage potential. Lee et al. (1992) investigated whether federal cost-sharing programs for tree planting on private lands had discouraged investments in tree planting by others, finding that there was no strong evidence for such leakage. Wu (2000) examined the potential leakage within the Conservation Reserve Program (CRP) and reported that on average about 20% of the acreage enrolled in the CRP was offset by expansion of cropland cultivated elsewhere.

In general, the existing literature on forest conservation leakage has focused on local-, regional- or country-level implications but has not treated the issue globally. This paper will expand the literature by estimating global transnational leakage. We develop an analytical framework for measuring leakage and construct simulation-based estimates of its magnitude for major forest countries/regions in the world using a computable general equilibrium (CGE) model open to trade. This approach allows for the consideration of both interregional and intersectoral effects of forest conservation.

2. Theoretical framework

A change in timber production in one country is likely to induce output reactions in other countries due to market linkages. Thus when forest conservation in one country reduces timber harvest in that country the market is likely to cause this to be offset by increased production elsewhere, resulting in leakage. In this study, forest conservation leakage is defined as dQ/dq, where dq is the reduced timber harvest in the host country and dQ is the resultant net change in total timber production in all other countries.

For illustration, let us start with a two-country, free trade case (Fig. 1). The supply and demand curves for the two countries are denoted by SC_i and DC_i (i=1, 2), respectively. Assume that country II has an excess demand for forestry

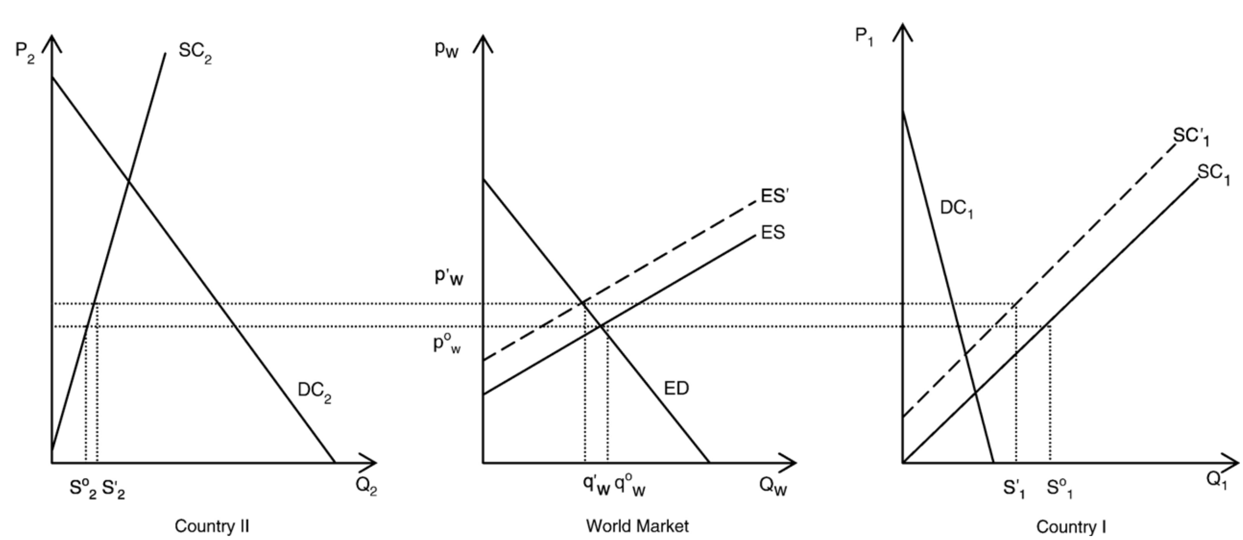

Fig. 1 – Forest conservation leakage in the two-country case.

products, while country I has an excess supply. The world price (p_w) is determined by equating excess demand to excess supply. Now suppose that country I (the host country) implements a forest conservation program (e.g. delaying harvest or adopting higher forest management standards) that increases its forestry production cost. As a result, the supply curve for country I shifts upwards from SC_1 to SC'_1 and the excess supply curve shifts upwards from ES to ES′ while the other curves are unchanged. In turn, the world price rises from p^o_w to p'_w, and the volume of trade between the two countries declines from q^o_w to q'_w. Consequently, country I's production falls from S^o_1 to S'_1, while country II's production increases from S^o_2 to S'_2. The net change in total world production, $(S^o_1-S'_1)+(S^o_2-S'_2)$ is smaller than the output reduction in country I, $(S^o_1-S'_1)$, implying that the conservation effort stimulates leakage. The magnitude of leakage (L) can be measured by the following ratio:

$$L=-\frac{S'_2-S^o_2}{S'_1-S^o_1}. \tag{1}$$

Obviously, the net conservation proportion for the two countries as a whole will be $(1-L)$.

Now we derive an analytical framework that quantifies leakage and reveals the key factors that determine leakage for a more general case involving n countries. Let $S_i(P_i, \theta_i)$ and $D_i(P_i)$ denote the supply and demand functions for country i, respectively, where P is the price and θ is the conservation effort. Assume that the supply curves are positively sloped with respect to price, but negatively sloped with respect to conservation, and that the demand curves are negatively sloped. Namely, $\frac{\partial S_i}{\partial P_i}>0$, $\frac{\partial S_i}{\partial \theta_i}<0$, $\frac{\partial D_i}{\partial P_i}<0, \forall i$. Global market equilibrium implies

$$\sum_{i=1}^{n}[S_i(P_i,\theta_i)-D_i(P_i)]=0. \tag{2}$$

Under free trade, $P_i=P$, $\forall i$. Without loss of generality, suppose that county 1 (the conservation hosting country) initiates or increases its conservation effort. Taking the partial derivative of Eq. (2) with respect to θ_1 yields

$$\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}\frac{\partial P}{\partial\theta_1}+\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}-\frac{\partial D_i}{\partial P}\frac{\partial P}{\partial\theta_1}\right)=0. \tag{3}$$

Rearranging Eq. (3), we derive

$$\frac{\partial P}{\partial\theta_1}=-\frac{\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}}{\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)}. \tag{4}$$

Given the standard assumptions about the slopes of the supply and demand curves as described earlier, if $\frac{\partial\theta_i}{\partial\theta_1}\geq 0 \forall i\neq 1$, then $\frac{\partial P}{\partial\theta_1}>0$. This indicates that the world price of forestry products will increase as country 1 (any individual country) initiates or increases its conservation effort if there is no intentional counter-cooperation in forest conservation among countries.

2.1. Leakage to another individual country

Taking derivatives of S_1 and S_j ($j\neq 1$) with respect to θ_1 leads to

$$\frac{dS_1}{d\theta_1}=\frac{\partial S_1}{\partial P}\frac{\partial P}{\partial\theta_1}+\frac{\partial S_1}{\partial\theta_1} \tag{5}$$

$$\frac{dS_j}{d\theta_1}=\frac{\partial S_j}{\partial P}\frac{\partial P}{\partial\theta_1}+\frac{\partial S_j}{\partial\theta_j}\frac{\partial\theta_j}{\partial\theta_1}. \tag{6}$$

Eq. (5) represents the change in country 1's output due to its own conservation effort. The output change consists of two parts: the direct effect of the conservation effort on output $\left(\frac{\partial S_1}{\partial\theta_1}\right)$ and the indirect effect of the conservation effort as it influences the price of forestry products $\left(\frac{\partial S_1}{\partial P}\frac{\partial P}{\partial\theta_1}\right)$. Though these two parts have opposite signs, it is rational to consider that the total effect on output has a negative sign. That is, the first term on the right hand side of Eq. (5) is small relative to the absolute value of the second term. This is particularly true when country 1 is a small country whose conservation effort would not affect the world price of forestry products much. Hence, a conservation effort in country 1 will ultimately reduce its forestry output.

Eq. (6) shows the reaction of country j's output to a change in country 1's conservation effort. The first term of Eq. (6) represents the output change due to the price alternation induced by country 1's conservation effort; the second term gauges the output change as country j adjusts its own conservation effort in response to country 1's conservation initiative.

Dividing Eq. (6) by Eq. (5) gives

$$\frac{dS_j}{dS_1}=\left(\frac{\partial S_j}{\partial P}\frac{\partial P}{\partial\theta_1}+\frac{\partial S_j}{\partial\theta_j}\frac{\partial\theta_j}{\partial\theta_1}\right)\bigg/\left(\frac{\partial S_1}{\partial P}\frac{\partial P}{\partial\theta_1}+\frac{\partial S_1}{\partial\theta_1}\right). \tag{7}$$

Eq. (7) measures the leakage to country j due to the conservation effort made in country 1, and it has a negative sign if leakage exits. As mentioned earlier, the denominator is negative. Thus, as long as the numerator is positive, leakage occurs. Obviously, the magnitude of leakage depends upon whether the two countries cooperate or not in forest conservation. The numerator will have a smaller value when $\frac{\partial\theta_j}{\partial\theta_1}>0$ than when $\frac{\partial\theta_j}{\partial\theta_1}\leq 0$, implying that leakage will be less severe if both counties work simultaneously to promote conservation (cooperate in conservation) than if there is no response or counter-cooperation by country j. Specifically, if conservation decisions in both countries are independent of each other $(\partial\theta_j/\partial\theta_1=0)$, the leakage is represented by $\frac{\partial S_j}{\partial P}\frac{\partial P}{\partial\theta_1}/\left(\frac{\partial S_1}{\partial P}\frac{\partial P}{\partial\theta_1}+\frac{\partial S_1}{\partial\theta_1}\right)$. There could be no leakage $(\partial S_j/\partial S_1\geq 0)$ if both countries work together (via simultaneously increasing their conservation efforts, i.e., $\partial\theta_j/\partial\theta_1>0$) to ensure $\frac{\partial S_j}{\partial\theta_j}\frac{\partial\theta_j}{\partial\theta_1}<-\frac{\partial S_j}{\partial P}\frac{\partial P}{\partial\theta_1}$. On the other hand, if county j intentionally counter-cooperates with country 1 (i.e., $\partial\theta_j/\partial\theta_1<0$), the numerator of Eq. (7) will certainly be positive, potentially leading to substantial leakage.

2.2. Leakage to all other countries

Summing Eq. (7) over j for all $j \neq 1$, we derive the total leakage to all other countries as follows:

$$\frac{dS_R}{dS_1} = \frac{\sum_{j\neq 1} dS_j}{dS_1} = \sum_{j\neq 1}\left(\frac{\partial S_j}{\partial P}\frac{\partial P}{\partial \theta_1} + \frac{\partial S_j}{\partial \theta_j}\frac{\partial \theta_j}{\partial \theta_1}\right)\Bigg/\left(\frac{\partial S_1}{\partial P}\frac{\partial P}{\partial \theta_1} + \frac{\partial S_1}{\partial \theta_1}\right). \tag{8}$$

Substituting Eq. (4) into Eq. (8) and simplifying it (see Appendix A), we have

$$\frac{dS_R}{dS_1} = \sum_{i=1}^{n} \frac{\partial D_i}{\partial P}\Bigg/\left(\frac{\partial S_1}{\partial P} - \beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P} - \frac{\partial D_i}{\partial P}\right)\right) - 1, \tag{9}$$

where

$$\beta \equiv \frac{\partial S_1}{\partial \theta_1}\Bigg/\sum_{i=1}^{n}\frac{\partial S_i}{\partial \theta_i}\frac{\partial \theta_i}{\partial \theta_1}. \tag{10}$$

The value of β depends upon how other countries react to the conservation initiative in country 1 and how sensitive the supply of forestry products in each country is to changes in conservation. We can call β the Coefficient of Strategic Conservation Reaction by all other countries to a conservation initiative in an individual country. It represents the intentional (strategic) reactions by other countries, not the reactions to the market/price signal. Obviously, β can be any real number.

According to Eq. (9), leakage is a rational function of β with a vertical asymptote of $\beta = \frac{\partial S_1}{\partial P}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P} - \frac{\partial D_i}{\partial P}\right)$ and a horizontal asymptote of $dS_R/dS_1 = -1$ (Fig. 2). The vertical asymptote will be close to zero if n is large and/or the supply and demand in all countries (except the supply in the conservation hosting country) are highly elastic. When $\left(\frac{\partial S_1}{\partial P} - \sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\right)\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P} - \frac{\partial D_i}{\partial P}\right) \geq \beta > \frac{\partial S_1}{\partial P}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P} - \frac{\partial D_i}{\partial P}\right)$, there will be no leakage ($dS_R/dS_1 \geq 0$); otherwise, some leakage exists. The magnitude of leakage will approach one (100% leakage) as β approaches $\pm\infty$, will be greater than one when $\beta < \frac{\partial S_1}{\partial P}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P} - \frac{\partial D_i}{\partial P}\right)$, and will reach its maximum (infinity) when β approaches $\frac{\partial S_1}{\partial P}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P} - \frac{\partial D_i}{\partial P}\right)$ from the left. Thus, tremendous leakage could take place if some countries counter-cooperate in conservation because such counter-cooperation possibly leads to $\beta > 1$ or even $\beta < \frac{\partial S_1}{\partial P}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P} - \frac{\partial D_i}{\partial P}\right)$. This also implies that leakage is not necessarily smaller when only some countries cooperate than when there is no cooperation at all because counter-cooperation by one or more countries can still make β very close to the vertical asymptote from the left.

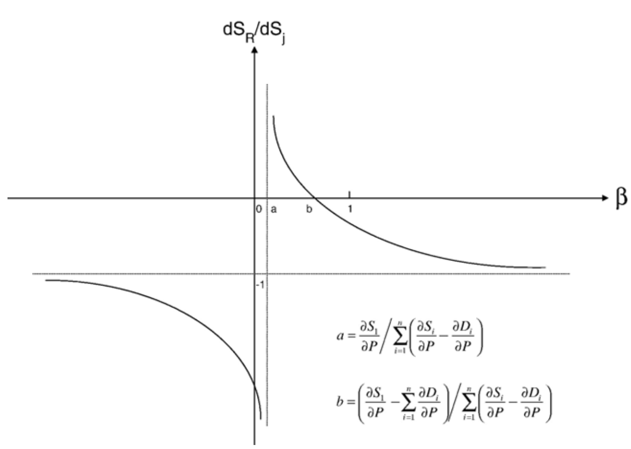

Fig. 2 – Leakage vs. the strategic conservation reaction coefficient (β).

Proposition I. *The magnitude of the total transnational leakage to all other countries due to a conservation effort in an individual country (country 1), as long as* $\beta \neq \frac{\partial S_1}{\partial P}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P} - \frac{\partial D_i}{\partial P}\right)$, *will*

(a) *fall as more countries cooperate (or fewer countries counter-cooperate) with country 1 in forest conservation;*
(b) *rise (fall) as the demand for forestry products in any country becomes more elastic with respect to price when* $\partial S_1/\partial P > \beta\sum_{i=1}^{n}\partial S_i/\partial P$ *(when* $\partial S_1/\partial P < \beta\sum_{i=1}^{n}\partial S_i/\partial P$*);*
(c) *fall (rise) as the supply of forestry products in country 1 (the conservation hosting country) becomes more elastic with respect to price when* $\beta < 1$ *(when* $\beta > 1$*); and*
(d) *rise (fall) as the supply of forestry products in any countries other than country 1 becomes more elastic with respect to price when* $\beta > 0$ *(when* $\beta < 0$*).*

Proof. Appendix B.

Now let us consider two special cases in a "nice" world (no counter-cooperation in conservation):

Case 1 – Conservation decisions between country 1 and any other country are independent (i.e., $\partial\theta_i/\partial\theta_1 = 0$, $\forall i \neq 1$).
Case 2 – All other countries cooperate with country 1 in forest conservation by increasing their conservation efforts simultaneously (i.e., $\partial\theta_i/\partial\theta_1 > 0$, $\forall i \neq 1$).

(a) Case 1

In this case, $\beta = 1$ since $\partial\theta_i/\partial\theta_1 = 0$ for all $i \neq 1$. Thus, Eq. (9) becomes

$$\begin{aligned}\frac{dS_R}{dS_1} &= \sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\Bigg/\left(\frac{\partial S_1}{\partial P} - \sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P} - \frac{\partial D_i}{\partial P}\right)\right) - 1 \\ &= -\sum_{i\neq 1}\frac{\partial S_i}{\partial P}\Bigg/\left(\sum_{i\neq}\frac{\partial S_i}{\partial P} - \sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\right).\end{aligned} \tag{11}$$

Obviously, $0 > \frac{dS_R}{dS_1} > -1$, and this suggests that the magnitude of the leakage is smaller than 1 if all other countries do not react (not intentionally/strategically changing its conservation effort) to the conservation initiated in country 1.

Proposition II. *If conservation decisions between a conservation hosting country (country 1) and any other country are independent, the magnitude of the total transnational leakage resulting from a conservation effort in country 1 will*

(a) *fall as the demand for forestry products in any country becomes more elastic with respect to price;*
(b) *be independent of the slope of the supply of forestry products in country 1; and*
(c) *rise as the supply of forestry products in any countries other than country 1 becomes more elastic with respect to price.*

Proof. Appendix C.

(b) Case 2

In this case, according to Eq. (10) $0 < \beta < 1$ since $\partial\theta_i/\partial\theta_1 > 0$, $\forall i \neq 1$. Thus, we derive the following proposition.

Proposition III. *If all countries cooperate in conservation (i.e., they simultaneously increase their conservation efforts), the magnitude of the total transnational leakage resulting from a conservation effort in an individual country (country 1) will*

(a) *rise (fall) as the demand for forestry products in any country becomes more elastic with respect to price when* $\partial S_1/\partial P > \beta\sum_{i=1}^{n}\partial S_i/\partial P$ *(when* $\partial S_1/\partial P < \beta\sum_{i=1}^{n}\partial S_i/\partial P$*);*
(b) *fall as the supply of forestry products in country 1 (the conservation hosting country) becomes more elastic with respect to price; and*
(c) *rise as the supply of forestry products in any countries other than country 1 becomes more elastic with respect to price.*

Proof. Appendix D.

The price elasticity of supply in the conservation hosting country has an influence on leakage in case 2, whereas it has no effect in case 1. This is primarily because the interactions among countries in their conservation decisions make the supply curves in all countries relevant, which is evidenced by comparing Eqs. (9) and (11). Also, the effect of the price elasticity of demand becomes ambiguous, depending upon the sign of $\partial S_1/\partial P - \beta\sum_{i=1}^{n}\partial S_i/\partial P$. Moreover, leakage is smaller in case 2 than in case 1 according to (a) of Proposition I. Thus, as explained earlier, cooperation among countries trends to reduce leakage as β gets smaller.

3. Numerical estimation

In addition to the above analytical leakage results, we also estimated leakage magnitudes in the global economy context. We employed a computable general equilibrium model, the Global Trade Analysis Project (GTAP) model (Hertel, 1997) for this estimation. The model enabled us to go beyond our analytical framework by accounting for intersectoral as well as interregional interactions in the economy. Version 6 of the GTAP database was used, which contains data for 57 sectors (commodity groups) and 87 countries/regions with a base year of 2001.

The original GTAP model is a comparative statics model. It portrays the behavior of economic agents such as regional households (private households and governments) and firms under the assumptions of market equilibrium and perfect competition. Regional households generate incomes from land, labor, capital, natural resources, and taxes. Total regional income is allocated to private household consumption, government consumption, and savings based on a Cobb–Douglas per capita utility function. Profit-maximizing firms are assumed to use primary factors and intermediate inputs to produce final goods and services in a nested constant elasticity of substitution (CES) production structure, which implies constant returns to scale. Products are differentiated by country of origin using the Armington (1969) structure. The private households, firms, and governments in different regions interact with one another through trade.

Global trade and associated transportation costs are also considered in the model. Transportation service is compensated with the difference between the f.o.b. (free on board) and c.i.f. (cost, insurance, and freight) values. Investment goods are allocated to all firms and households according to savings and rates of return on capital by a hypothetical global bank. The structure and behavioral equations of the GTAP model can be found in Hertel (1997).

For this study the GTAP countries/regions were aggregated into 10 broad regions according to their importance in the world's production, consumption, and trade of forest products; current forest conditions and management practices; economic development status; and geographic location. These regions were the United States of America (USA), Canada (CAN), the European Union (EU), Australasia (ANZ), East Asia (EAS), Southeast Asia (SEA), Latin America (LAM), Russia (RUS), Sub-Saharan Africa (SSA), and the rest of the world (ROW). Commodities were aggregated into 10 sectors: forestry (FOR), lumber and wood products (LUM), pulp and paper (PPR), agriculture and food (AGF), agriculture-based fiber (FBR), plastic products (PLS), metal products (MTL), mining and energy (MNG), manufacturing (MNF), and services (SVS), reflecting the study emphasis on forestry and related sectors. More detailed descriptions of these sectors and regions are presented in Table 1.

The responses to an output change in a specific region (no conservation cooperation among countries/regions) or a group of regions (conservation cooperation among some countries/regions) by other regions were simulated by directly shocking the forestry output of the region. To meet the model closure requirement, the output variable was swapped with the output tax, an exogenous variable in the standard GTAP model. This approach was followed since forest conservation and environmental protection (e.g., adopting higher forest

Table 1 – Regional and sectoral aggregation

Regional identifier	Country/region	Sectoral identifier	Sector
USA	The United States of America	FOR	Forestry
CAN	Canada	LUM	Lumber and wood products
EU	The European Union (including only the former 15 EU countries)	PPR	Pulp, paper, and allied products
ANZ	Australasia (Australia and New Zealand)	AGF	Agriculture and food processing
EAS	East Asia including Japan, China, Hong Kong, Taiwan, Korea, and Singapore	FBR	Plant-based fiber, wool, silk-worm cocoons
SEA	Southeast Asia	PLS	Chemical, rubber, and plastic products
LAM	Latin America	MTL	Ferrous metals, metal necessities, and metal products
SSA	Sub-Saharan Africa	MNG	Mining and primary energy
RUS	Russia	MNF	Manufacturing
ROW	The rest of the world (all the remaining countries in the GTAP database)	SVS	Services

Table 2 – Characteristics of the forestry sector and markets in different countries/regions

Country/ region	Share in total world output (%)	Share in total world exports (%)	Share in total world imports (%)	Percent of output exported	Percent of imports in domestic consumption	Import tariffs (%)
USA	13.58	12.82	3.21	7.04	2.02	0.03
CAN	8.75	3.90	3.95	3.32	3.65	0
EU	13.91	15.65	34.56	8.39	18.01	0.03
ANZ	1.90	7.90	0.15	30.98	0.95	0.61
EAS	20.18	1.54	41.53	0.57	14.41	0.43
SEA	5.81	13.74	2.69	17.63	4.38	0.66
LAM	6.29	2.63	0.92	3.12	1.26	4.16
SSA	8.30	14.17	0.41	12.73	0.47	2.98
RUS	2.58	16.50	0.24	47.69	1.48	4.69
ROW	18.70	11.14	12.35	4.44	5.55	5.07
The world total	100	100	100	7.45	8.11	0.89

Source: GTAP database v6.
Note: The country/region acronyms are shown in Table 1.

management standards) in an individual country/region would lead to an increase in its forestry production cost and thus making the output tax endogenous allows for mimicking cost changes as the output is altered.

The estimation was based on current global and regional market conditions for forestry products. Table 2 shows the characteristics of regional forestry sectors/markets and their role in global markets. The dependence of the forestry sector on trade varies considerably across countries/regions; and tariffs for forestry products are generally low.

A systematic sensitivity analysis was conducted to examine the sensitivity of the leakage estimates to changes in model parameters. We focused on the response of the leakage estimates to changes in the elasticity of substitution between domestic and imported forestry products since the Armington elasticity of substitution is one of the key parameters in the GTAP model. Additionally, the sensitivity analysis also provides hints about the possible influence of national production differentiation on leakage, which is not considered in our analytical framework for the reason of tractability. The analysis was performed via Gaussian quadrature (Arndt, 1996), which treats the exogenous parameter as a random variable and estimates the means and standard deviations of model results. Based on the means and standard deviations, we then calculated the 95% confidence intervals of leakage rates.

4. Simulation results

Table 3 shows the transnational leakage derived from the GTAP model simulation. The leakage was measured as the ratio of the net output change in all other regions to the reduction in forestry production in a specific country/region or a group of countries/regions. This reduction was held equal to one.

If there is no conservation cooperation between any two countries, of all the countries/regions modeled, Russia would have the highest leakage rate (95%) whereas Canada would have the lowest (42%). Most of the reduced timber production in Russia would be displaced by increased production in East Asia (28%[2]), the EU (21%), and the rest of the world (12%). This mirrors the fact that most of Russian timber exports currently go to East Asia and the EU. Almost all the countries/regions (except for Canada) have a leakage rate of at least 65%. This suggests that global net gain from forest conservation in an individual country is quite modest, in general less than 35%. Of all the countries/regions, forest conservation (in terms of timber production reduction) in Canada is likely to generate the highest net gain for the world. Thus from a global perspective Canada is the most effective place to carry out forest conservation. The relatively low leakage for Canada might be partly because Canada plays only a very limited role in global log markets (both import and export) (Table 2) although it is a big player in global processed wood products (lumber and paper) markets.

Probably more disturbing is that a significant portion of the reduced forestry production in developed countries implementing conservation would be transferred to developing countries where forest conservation is often argued to be critically needed. The majority of current deforestation occurs in developing countries, particularly in tropical regions often involving rainforests and these are subject to substantial forest-related environmental concerns (Food and Agriculture Organization, 2006). The results show 75% of the reduced timber harvest in the EU, 70% of that in Australia and New Zealand, and 46% in the US is transferred to developing countries, mainly tropical forest regions. The majority of reduced timber production in the EU would be offset by increased production in the rest of the world (30%), Southeast Asia (16%), and Russia (10%). The main countries/regions that would displace timber production in Australia and New Zealand would be East Asia (36%), Southeast Asia (12%), and the US (10%). East Asia (20%) and Canada (20%) would displace most of the reduced timber production in the US. The high leakage rates call into question the effectiveness of forest

[2] The percent inside parentheses in this section indicates the proportion of the output reduction that leaks out to the country/region. For instance, here it means that 28% of the reduced production in Russia would be offset by East Asia.

Table 3 – Transnational leakage in forestry production

Country/region	Leakage to outside of USA, CAN, EU and ANZ	Total leakage
No conservation cooperation among countries/regions		
USA	0.458	0.767
CAN	0.210	0.423
EU	0.750	0.861
ANZ	0.697	0.890
EAS	0.368	0.698
SEA	0.503	0.762
LAM	0.337	0.742
SSA	0.499	0.872
RUS	0.584	0.954
ROW	0.314	0.650
Cooperation among some countries/regions		
USA, CAN, EU and ANZ	0.639	0.639
SEA, LAM and SSA	0.395	0.779

Note: The leakage is measured with the total net change in forestry output in all other countries/regions due to a unitary reduction in forestry output in a specific country/region listed in the first column. The country/region acronyms are shown in Table 1.

Table 4 – Intersectoral effects of forest conservation

Country/region	LUM	PPR	FBR	PLS	MTL
USA	-0.090	0.004	0.009	0.003	0.008
CAN	-0.892	-0.089	0.030	0.089	0.115
EU	-0.136	-0.016	0.015	0.010	0.011
ANZ	-0.136	0.000	0.012	0.018	0.023
EAS	-0.357	0.005	0.021	-0.009	0.019
SEA	-0.782	0.029	0.037	0.053	0.042
LAM	-0.634	0.000	0.031	0.016	0.039
SSA	-0.206	-0.004	0.142	0.070	0.165
RUS	-0.177	-0.045	0.017	0.035	0.037
ROW	-0.433	-0.042	0.025	0.025	0.038
USA, CAN, EU and ANZ	-0.123	-0.009	0.009	0.004	0.011
SEA, LAM and SSA	-0.652	0.004	0.076	0.033	0.059

Note: The figures in this table represent the percentage changes in the sector's output within the country/region due to a 1% change in its forestry output. The country/region and sector acronyms are shown in Table 1.

conservation implemented by individual countries if without international cooperation to alleviate such leakage.

We also estimated the leakage when the US, Canada, the EU, and Australia cooperate in conservation and when the tropical forest regions cooperate. The leakage estimates under cooperation among these countries alone are not much different from those without cooperation among them (Table 3). This echoes our theoretical result that cooperation among some (not all) countries may not necessarily dramatically reduce leakage.

A 1% reduction in forestry output in any individual country would have a very small impact on the world price of forestry products (<0.5% increase), and its impacts on the world prices of lumber and paper products would be even more moderate (<0.1%). Only when all countries in the world simultaneously reduce forestry output, would the world price of forestry products increase at some noticeable level. For a 1% reduction in forestry output in all countries, the world prices of forestry products, lumber and wood products, and pulp and paper products would go up by 8.5%, 0.9%, and 0.1%, respectively.

In addition to transnational leakage, we also assessed the intersectoral effects of forest conservation via CGE simulations. In terms of the downstream sectors, forest conservation would have some negative impacts on the output of the lumber and wood products sector within the conservation hosting country whereas its effects on the pulp and paper sector would be moderate. Moreover, its impacts on the production of its potential substitutes like plant-based fibers, plastics, and metals would generally be negligible except for Sub-Saharan Africa where reductions in timber production could result in noticeable increases in the production of plant-based fibers and metals (Table 4).

These leakage estimates can also be used in estimating the net contribution of local or regional forest carbon sequestration projects to the global carbon pool. From the perspective of carbon sequestration, the high leakage rates reveal the ineffectiveness of local or regional forest carbon sequestration projects if no mechanism is implemented to prevent this leakage. Given the high leakage, it is imperative to take leakage into account in evaluating the carbon benefits of local or regional forest projects.

The 95% confidence intervals of the leakage estimates for a 10% change (increase and decrease) in the elasticity of substitution between domestic and imported forestry products for all countries/regions are shown in Table 5. The standard deviations of leakage are less than 2% of the means for all countries/regions, revealing the robustness of the leakage estimates. The relative insensitiveness of leakage to changes in the elasticity of substitution also suggests that omitting national product differentiation would not cause large biases in leakage estimation, justifying (at least partially) the simplification (the assumption of perfect substitution among forestry products originating in different countries/regions) adopted in deriving our theoretical framework earlier.

Table 5 – The 95% confidence intervals of leakage estimates for a 10% change in the elasticity of substitution between domestic and imported forestry products for all countries/regions

Country/region	Leakage to outside of USA, CAN, EU and ANZ	Total leakage
No conservation cooperation among countries/regions		
USA	(0.448, 0.468)	(0.752, 0.782)
CAN	(0.206, 0.215)	(0.410, 0.436)
EU	(0.742, 0.758)	(0.851, 0.871)
ANZ	(0.689, 0.704)	(0.879, 0.899)
EAS	(0.362, 0.374)	(0.686, 0.710)
SEA	(0.487, 0.520)	(0.739, 0.785)
LAM	(0.327, 0.346)	(0.722, 0.762)
SSA	(0.489, 0.508)	(0.857, 0.886)
RUS	(0.579, 0.588)	(0.947, 0.960)
ROW	(0.307, 0.321)	(0.638, 0.662)
Cooperation among some countries/regions		
USA, CAN, EU and ANZ	(0.629, 0.648)	(0.629, 0.648)
SEA, LAM and SSA	(0.386, 0.404)	(0.764, 0.795)

Note: The country/region acronyms are shown in Table 1.

5. Concluding remarks

Market interactions are often desirable because they help more efficiently allocate resources. Under some circumstances, however, such interactions may not be so desirable. One such case is the transboundary effects of forest conservation, which stems from the interactions of forest product markets in different locations. In this article, we analytically derive the transnational leakage of forest conservation due to market forces using a multiple-country model. Then we estimate the leakage via CGE modeling. Our analytical results reveal that the magnitude of leakage is related to the price elasticities of demand for and supply of forestry products in all countries and whether and how countries cooperate in forest conservation. Conservation cooperation among countries, in general, tends to alleviate leakage, yet cooperation among only some countries does not necessarily significantly reduce overall global leakage.

Our leakage estimation via CGE modeling examines leakage among countries and between sectors. Under the current global trade conditions and system, the estimated leakage rate ranges from 42% to 95% with a leakage rate of 70% or higher for most countries/regions. Hence, the gain from individual country forest conservation efforts is likely to be undermined if without a mechanism to prevent transnational leakage. Furthermore, a sizable portion (21% to 75%) of reduced timber harvest or conserved standing forest in developed country is offset by increased production/deforestation in developing, mainly tropical timber producing countries, increasing tropical deforestation and often the lamented "cutting down of the rainforest". Our simulation results also show that conservation cooperation among tropical forest regions or developed countries alone is not effective in curtailing global forest conservation leakage.

Our results offer some important insight into the effectiveness or ineffectiveness of local or regional forest conservation efforts from a global perspective and would be of value for measuring the net global contribution of forest carbon sequestration programs implemented in different countries. Here are some specific implications for global forest resource conservation.

- High leakage rates reduce the contribution of local or regional conservation efforts to global forest conservation. Simultaneously achieving cooperation among only a few countries does not always effectively lessen leakage. Hence, there is an urgent need for global cooperation and joint efforts in forest conservation.
- Reducing timber production in developed countries would not be an effective way of enhancing global forest conservation as a large percent of the reduced forestry production would be transferred to developing countries. Therefore, policies that encourage forestry production in developed countries or discourage the transfer of wood processing capacity to developing countries might do more good than harm to global forest conservation, especially as developed countries are generally more efficient than other countries in timber production and wood and paper manufacturing.
- Leakage would be a valuable item to estimate when considering forest carbon sequestration as the net gain from individual forest carbon sequestration projects may be substantially smaller when considered on a global scale.

Our simulation results are influenced by the underlying assumptions and configuration of the GTAP model, including perfect competition, equilibrium in all markets, and constant elasticity of substitution. These restraints could be relaxed with some modification. Similarly, the theoretic model can be extended by introducing intersectoral linkages, imperfect substitution between domestic and imported products, and trade policy, among others. We leave these tasks for future work.

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Appendix A

From Eq. (8), we have

$$\frac{dS_R}{dS_1}=\frac{\sum_{j\neq 1}\left(\frac{\partial S_j}{\partial P}+\frac{\partial S_j}{\partial\theta_j}\frac{\partial\theta_j}{\partial\theta_1}\Big/\frac{\partial P}{\partial\theta_1}\right)}{\frac{\partial S_1}{\partial P}+\frac{\partial S_1}{\partial\theta_1}\Big/\frac{\partial P}{\partial\theta_1}} \tag{A1}$$

Substituting Eq. (4) into Eq. (A1) yields

$$\frac{dS_R}{dS_1}=\frac{\sum_{j\neq 1}\left(\frac{\partial S_j}{\partial P}+\frac{\partial S_j}{\partial\theta_j}\frac{\partial\theta_j}{\partial\theta_1}\Big/\left(-\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\right)\right)}{\frac{\partial S_1}{\partial P}+\frac{\partial S_1}{\partial\theta_1}\Big/\left(-\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\right)}$$

$$=\frac{\sum_{j\neq 1}\left(\frac{\partial S_j}{\partial P}-\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_j}{\partial\theta_j}\frac{\partial\theta_j}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}\right)}{\frac{\partial S_1}{\partial P}-\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_1}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}}$$

$$=\frac{\sum_{j\neq 1}\frac{\partial S_j}{\partial P}-\sum_{j=1}^{n}\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_j}{\partial\theta_j}\frac{\partial\theta_j}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}+\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_1}{\partial\theta_1}\frac{\partial\theta_1}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}}{\frac{\partial S_1}{\partial P}-\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_1}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}}$$

$$=\frac{\sum_{j\neq 1}\frac{\partial S_j}{\partial P}-\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)+\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_1}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}}{\frac{\partial S_1}{\partial P}-\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_1}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}}$$

$$=\frac{\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}-\frac{\partial S_1}{\partial P}+\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_1}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}}{\frac{\partial S_1}{\partial P}-\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_1}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}}$$

$$=\frac{\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}}{\frac{\partial S_1}{\partial P}-\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\frac{\partial S_1}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}}-1$$

$$=\frac{\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}}{\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)}-1, \tag{A2}$$

where $\beta\equiv\frac{\partial S_1}{\partial\theta_1}\Big/\sum_{i=1}^{n}\frac{\partial S_i}{\partial\theta_i}\frac{\partial\theta_i}{\partial\theta_1}$.

Appendix B

Proof of Proposition I. Taking partial derivative of Eq. (9) with respective to β yields

$$\frac{\partial}{\partial\beta}\left(\frac{dS_R}{dS_1}\right)=\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\Big/\left(\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\right)^2. \tag{B1}$$

Eq. (B1) is negative as long as the denominator is not equal to zero, i.e., $\beta\neq\frac{\partial S_1}{\partial P}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)$.

Given that $dS_R/dS_1<0$ when leakage exists, i.e., when $\beta>\left(\frac{\partial S_1}{\partial P}-\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\right)\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)$ or $\beta<\frac{\partial S_1}{\partial P}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)$, the magnitude of leakage increases with the value of β. According to Eq. (10), β will become smaller as more countries cooperate or fewer countries counter-cooperate or do not react to country 1's conservation initiative since $\partial\theta_i/d\theta_1>0$ for a cooperating country, $\partial\theta_i/d\theta_1<0$ for a counter-cooperating country, and $\partial\theta_i/d\theta_1=0$ for an independent country. Hence, (a) holds.

Taking partial derivative of Eq. (9) with respect to $\partial D_j/\partial P$ gives

$$\frac{\partial}{\partial(\partial D_j/\partial P)}\left(\frac{dS_R}{dS_1}\right)=\left[\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)-\beta\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\right]\Big/\left[\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\right]^2=\left(\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\frac{\partial S_i}{\partial P}\right)\Big/\left[\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\right]^2. \tag{B2}$$

The sign of Eq. (B2) is ambiguous, depending upon the sign of $\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\frac{\partial S_i}{\partial P}$. An increase in $\partial D_j/\partial P$ (i.e., the demand in country j becomes less elastic with respect to price) will cause dS_R/dS_1 to increase, remain unchanged, or decrease when $\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\frac{\partial S_i}{\partial P}>,=,\text{or}<0$. Since the magnitude of leakage is the absolute value of dS_R/dS_1, this proves (b).

By taking partial derivative of Eq. (9) with respect to $\partial S_1/\partial P$, we have

$$\frac{\partial}{\partial(\partial S_1/\partial P)}\left(\frac{dS_R}{dS_1}\right)=(\beta-1)\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\Big/\left[\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\right]^2. \tag{B3}$$

The sign of Eq. (B3) depends upon the sign of $(\beta-1)$. Eq. (B3) is positive (negative or equal to zero) when $\beta<1$ (>1 or $=1$). This leads to the proof of (c).

Similarly, taking partial derivative of Eq. (9) with respect to $\partial S_j/\partial P$ for $j\neq1$ gives

$$\frac{\partial}{\partial(\partial S_j/\partial P)}\left(\frac{dS_R}{dS_1}\right)=\beta\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\Big/\left[\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\right]^2 \tag{B4}$$

Apparently, Eq. (B4) is positive (negative or equal to zero) when $\beta<0$ (>0 or $=0$). This proves (d).

Appendix C

Proof of Proposition II. Proofs for (a) and (b) follow immediately from Eq. (11) by inspection.

To prove (c), substituting $\beta=1$ into Eq. (B4) yields

$$\frac{\partial}{\partial(\partial S_j/\partial P)}\left(\frac{dS_R}{dS_1}\right)=\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\Big/\left(\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}-\sum_{i\neq1}\frac{\partial S_i}{\partial P}\right)^2<0. \tag{C1}$$

This indicates that dS_R/dS_1 falls as $\partial S_j/\partial P$ rises. Given the negative sign of dS_R/dS_1, this suggests that the magnitude of leakage increases as the price elasticity of supply for country j increases, leading to the proof of (c).

Appendix D

Proof of Proposition III. In this case, $0<\beta<1$. Actually, when all countries cooperate, it is impossible to cause too large leakage. Thus, $\beta>\frac{\partial S_1}{\partial P}\Big/\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)$.

Proof of (a) follows directly from Eq. (B2).

According to Eq. (B3) and recalling $\beta<1$, we derive

$$\frac{\partial}{\partial(\partial S_1/\partial P)}\left(\frac{dS_R}{dS_1}\right)=(\beta-1)\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\Big/\left[\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\right]^2>0 \tag{D2}$$

Therefore, (b) holds.

Similarly, following Eq. (B4) and recalling $\beta>0$ in this case, we derive

$$\frac{\partial}{\partial(\partial S_j/\partial P)}\left(\frac{dS_R}{dS_1}\right)=\beta\sum_{i=1}^{n}\frac{\partial D_i}{\partial P}\Big/\left[\frac{\partial S_1}{\partial P}-\beta\sum_{i=1}^{n}\left(\frac{\partial S_i}{\partial P}-\frac{\partial D_i}{\partial P}\right)\right]^2<0 \tag{D3}$$

This proves (d).

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